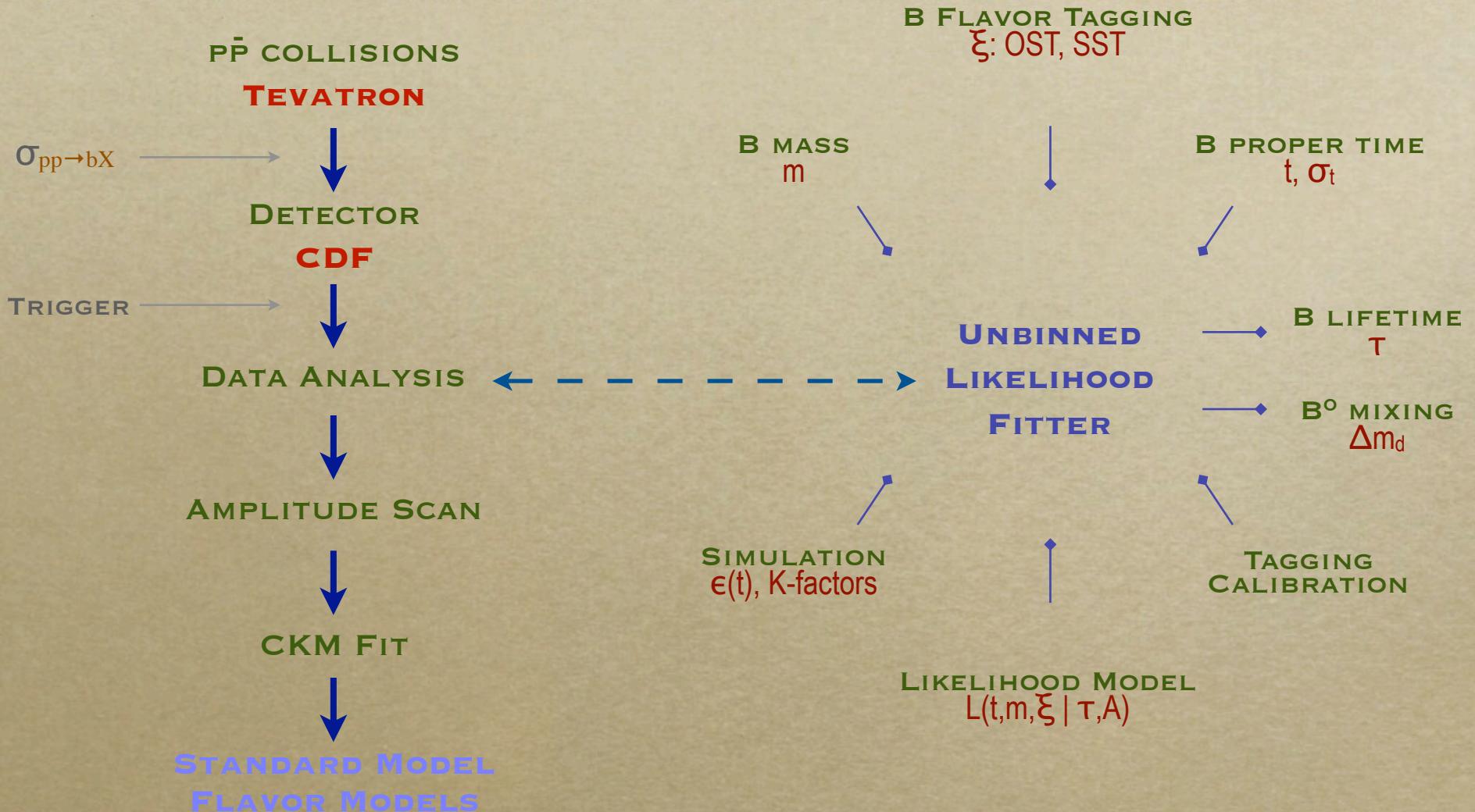


B_s Mixing at CDF

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FERMILAB, NOVEMBER 1ST 2005

Scope & Overview



Motivation

- Neutral B mesons flavor-oscillate with frequency given by

$$\Delta m = m_{B_H} - m_{B_L}$$

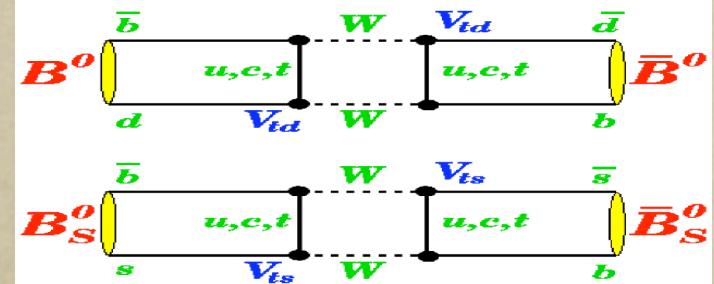
- Measure fundamental SM parameters

$$\Delta m_q \propto |V_{tq}|^2$$

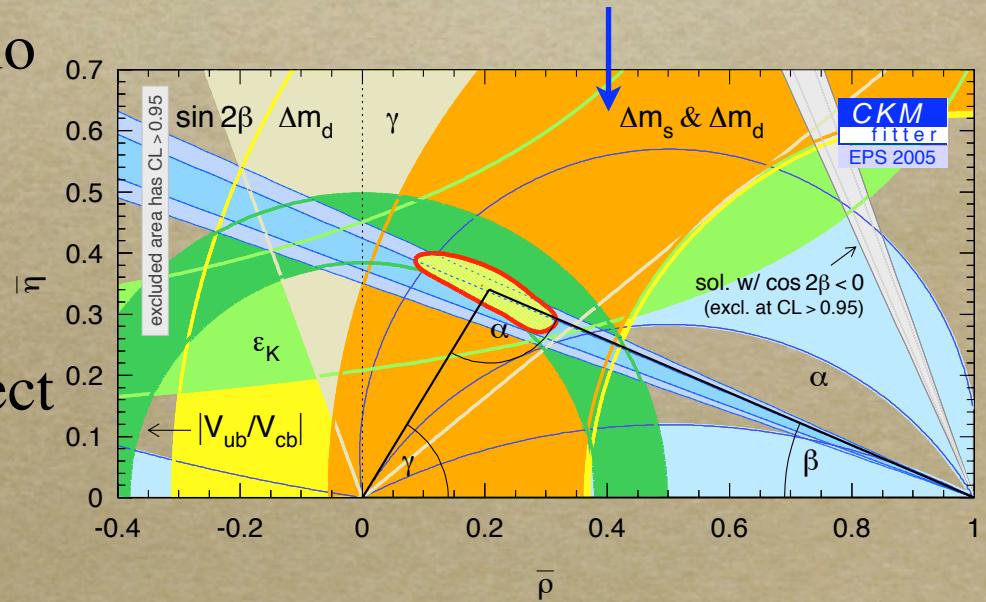
- Hadronic uncertainties cancel in ratio
 - improved lattice computation:

$$\xi = 1.21 \pm 0.022^{+0.035}_{-0.014}$$

- New Physics may have sizeable effect

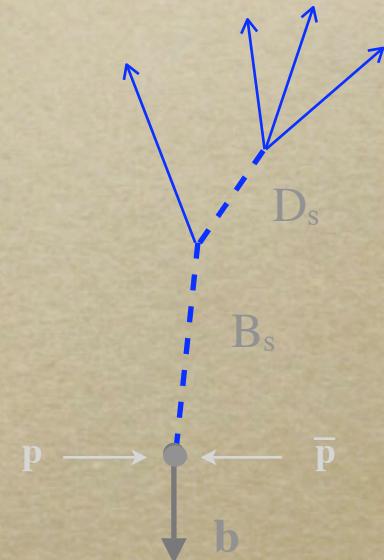


$$\frac{\Delta m_s}{\Delta m_d} = \frac{m_{B_{B_s}}}{m_{B_{B_d}}} \xi^2 \frac{|V_{ts}|^2}{|V_{td}|^2}$$



Mixing ingredients

- **B samples**
 - collect events with displaced tracks and vertices
 - reconstruct decay modes: $B_s \rightarrow D_s(3)\pi$ and $B_s \rightarrow 1 D_s X$
- **B proper decay time**
 - measure distance between production and decay
 - determine B_s meson's momentum
- **B flavor at production**
 - established by flavor tagging methods
 - determine probability that tag is correct
- **Likelihood description for unbinned fitting**
 - signal and background components in mass and ct space
 - trigger and selection bias in proper decay time



Contributions to mixing

$$S_{\text{significance}} \sim \sqrt{\frac{S \cdot \epsilon D^2}{2}} \cdot \sqrt{\frac{S}{S + B}} \cdot e^{-\frac{(\Delta m - \sigma_t)^2}{2}}$$

Signal yield **Tagging** **Purity** **ct-resolution**



- ct-resolution $\sigma_t = \sigma_l \oplus t\sigma_p$
- vertex resolution (σ_l), measured per-event
- momentum resolution (σ_p): scales with ct
 - ▶ negligible for fully reconstructed modes
 - ▶ important effect in partially reconstructed decays

Samples

Signal selection

Online selection: trigger

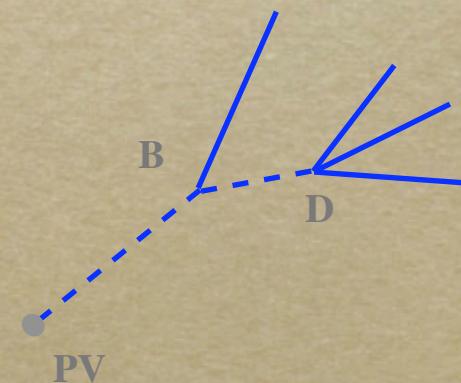
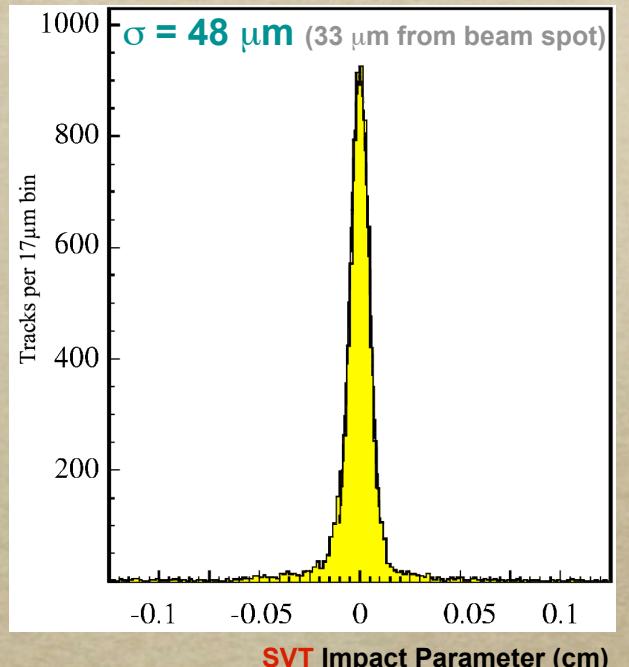
Select displaced-tracks and vertices

- Silicon Vertex Trigger (SVT)
- $p_T > 2 \text{ GeV}/c$, $\sum p_T > 5.5 \text{ GeV}/c$
- $120 \mu\text{m} < d_0 < 1 \text{ mm}$, at Trigger Level 2
- $L_{xy} > 200 \mu\text{m}$

Offline selection: signal reconstruction

Cut based optimization of $S^2/(S+B)$
using quantities of fully reconstructed objects
including:

- quality of vertex fits of D and B candidates
- displacement of vertices: L_{xy} , $L_{xy}/\sigma_{L_{xy}}$
- mass, transverse momenta of reconstructed particles
- lepton identification likelihoods



Hadronic samples $B_s \rightarrow D_s(3)\pi$

- Channels

$B_s \rightarrow D_s^- \pi^+$, with $D_s \rightarrow \Phi \pi^-, K^* K, 3\pi$

$B_s \rightarrow D_s^- \pi^+ \pi^- \pi^+$, with $D_s \rightarrow \Phi \pi^-, K^* K$

- Yield

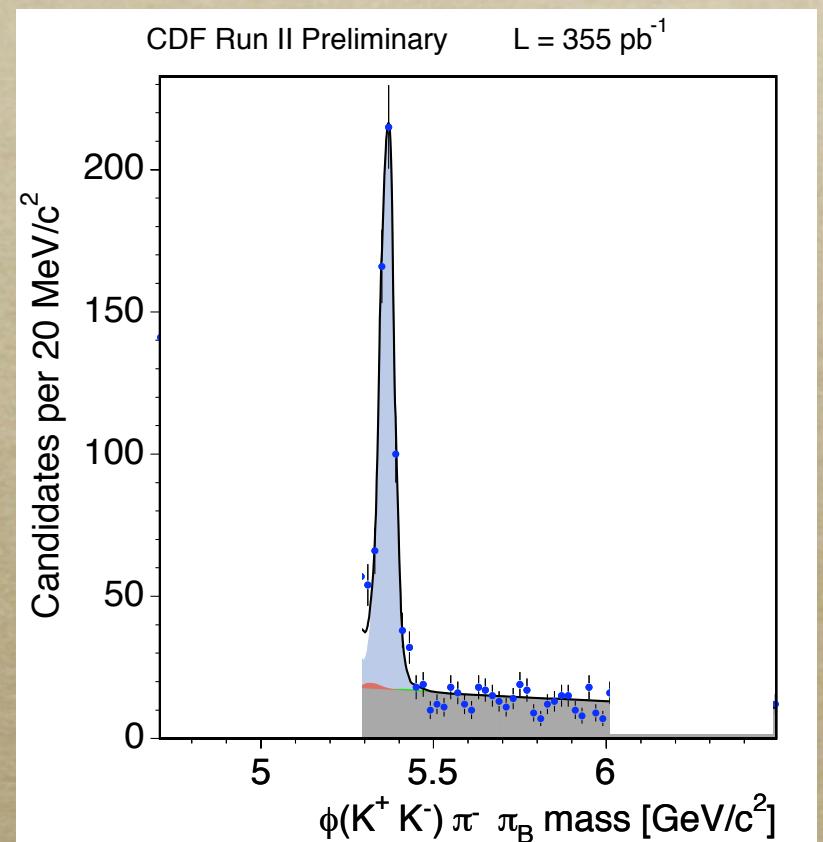
$S \sim 1100$, $S/B \sim 3.4$

- Fit performed in narrow mass range

 - exclude region with satellites

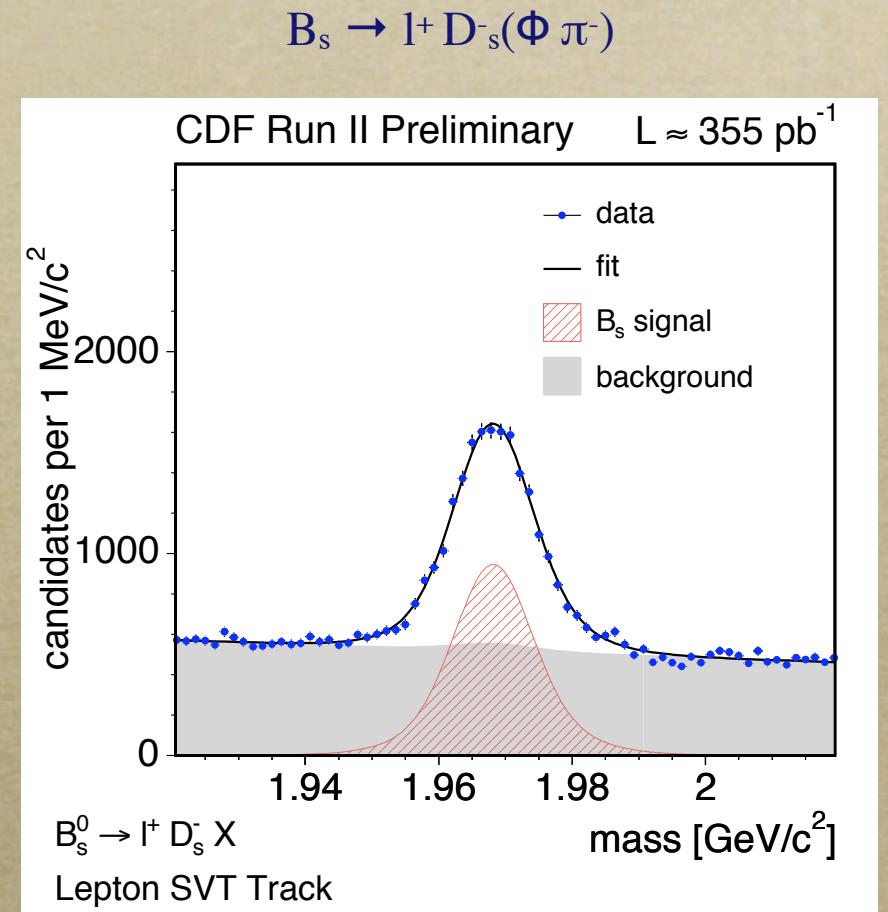
- Smaller statistics, better ct resolution

$B_s \rightarrow \pi^+ D_s^- (\Phi \pi^-)$



Semileptonic samples $B_s \rightarrow l^- D_s^+ X$

- Channels
- $B_s \rightarrow D_s^- l^+ X$, with $D_s \rightarrow \Phi \pi^-, K^* K, 3\pi$
- Yield
- $S \sim 15000, S/B = 2.3$
- B_s is only partially reconstructed
 - use D_s mass together with $l^- D_s$ charge correlation
- Larger statistics, worse ct resolution



Decay time

Proper decay time $t = L m/p$

• Proper time, t

$$t = L_{xy} \frac{M_{B_s}}{p_T}$$

• Lifetime, τ

$$P(t) = \frac{1}{\tau} e^{-\frac{t}{\tau}}$$

• t-resolution, σ_t

$$\otimes G(t|\sigma_t)$$

• Mixing, Δm

$$P_{mix} \sim 1 - \cos(\Delta m_s t)$$

• Tagging, D

$$P_{mix} \sim 1 - D \cdot \cos(\Delta m_s t)$$

Trigger and selection ct-bias

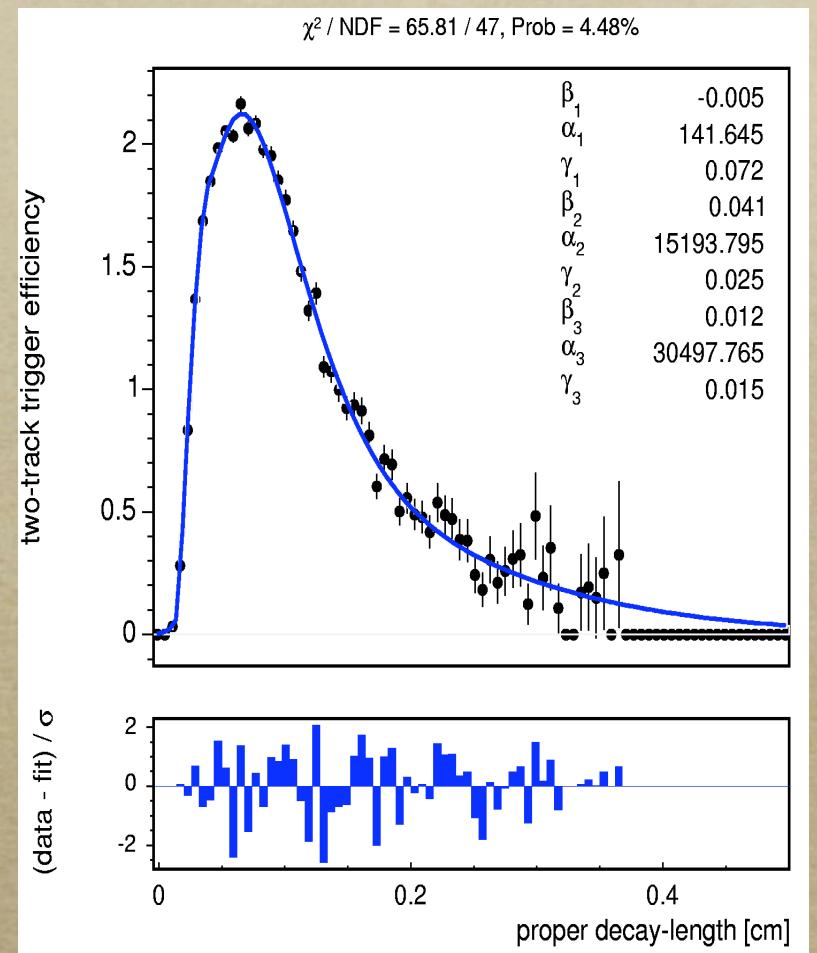
- Trigger and event selection *sculpt* proper time distribution
- Effect is described by **ct-efficiency** curve obtained from Monte Carlo

$$\epsilon(t) = \frac{t \text{ after trigger + cuts}}{\sum e^{-\frac{t}{\tau}} \otimes G(\sigma_t)}$$

- Used to correct proper time PDF

$$\left[\frac{1}{\tau} e^{-\frac{t}{\tau}} \otimes G(\sigma_t) \right] \cdot \epsilon(t)$$

- Choose parameterization allowing analytical integration of PDF normalization!



Kinematic correction in $B_s \rightarrow l D_s X$

- Determination of B_s momentum is incomplete in semileptonic modes
 - e.g. due to missing neutrino

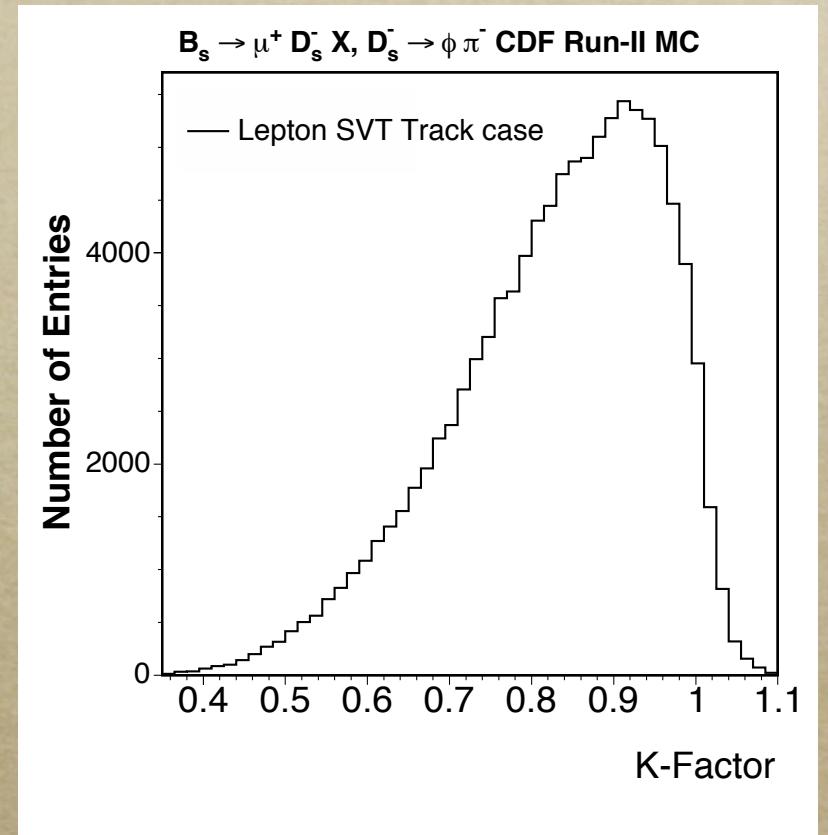
- Include **K_{kinematical}-factor** from MC

$$t_B = t \cdot K \quad \text{with} \quad K = \frac{p_T(lD_s)}{p_T(B_s)}$$

- Distribution F(K) used in likelihood

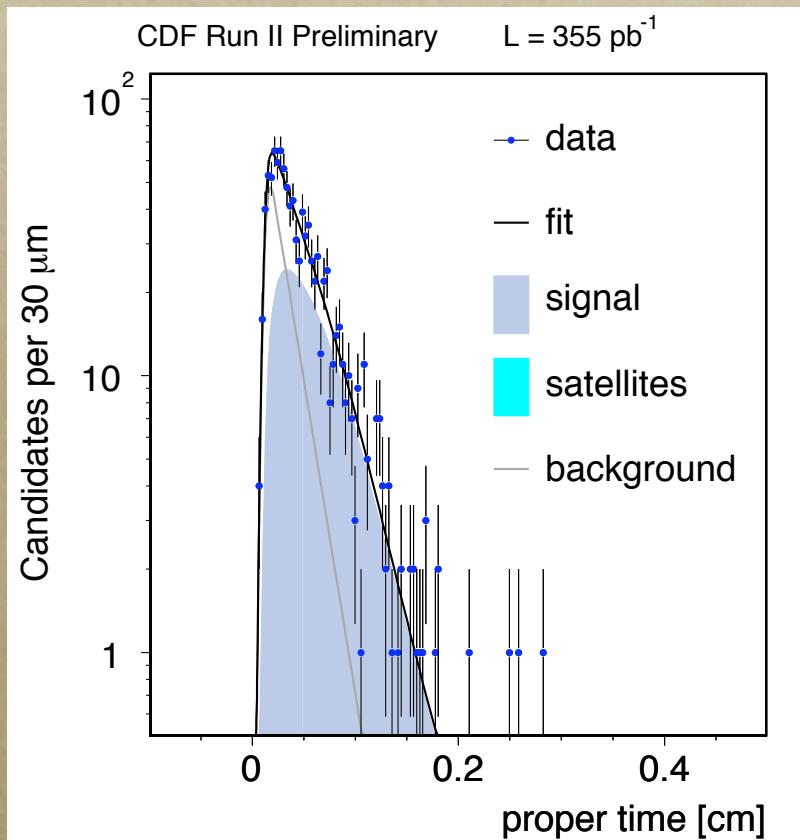
$$\frac{1}{\tau} e^{-\frac{t}{\tau}} \rightarrow \int \frac{K}{\tau} e^{-\frac{Kt}{\tau}} F(K) dK$$

- Explore K dependency on $m(lD_s)$
- Worsens resolution in ct space

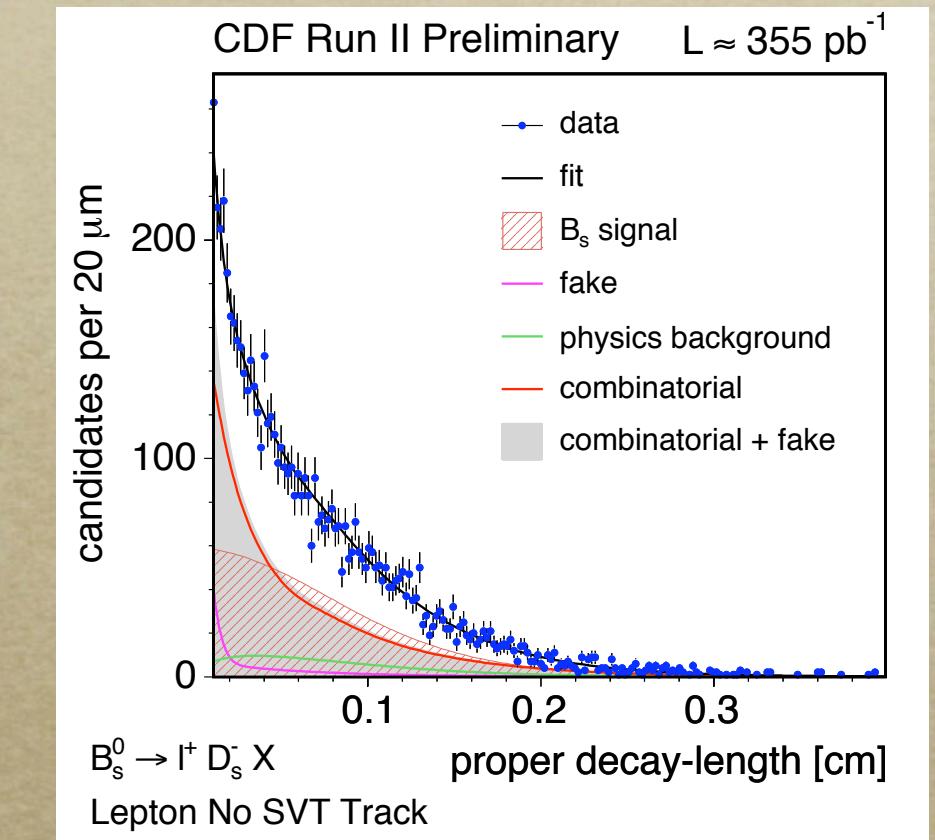


Lifetime fit

Hadronic



Semileptonic



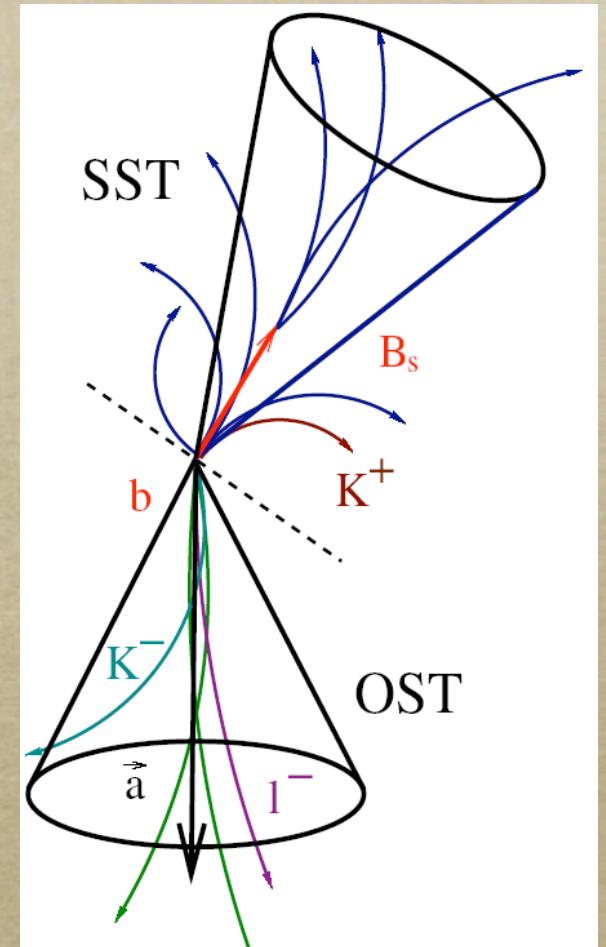
The measured B_s lifetimes are in good agreement with the PDG value

$$c\tau(B_s) = 439.5 \pm 17.7 \mu\text{m} \text{ [PDG 2005]}$$

Flavor tagging

Tagging B production flavor

- Establish whether B originated from b or \bar{b}
- Two classes of flavor taggers:
 - **Opposite-Side** (based on properties of the *non-reconstructed b-hadron*)
 - **Same-Side** (not used at current stage)
- Use exclusive combination of OSTs:
 - Lepton taggers: muon, electron
 - ▶ semileptonic decay of opposite side b
 - Jet charge taggers: displaced vertex, jet probability, highest p_T
 - ▶ identify charge of opposite side b jet



Tagging calibration

Tagging power: ϵD^2

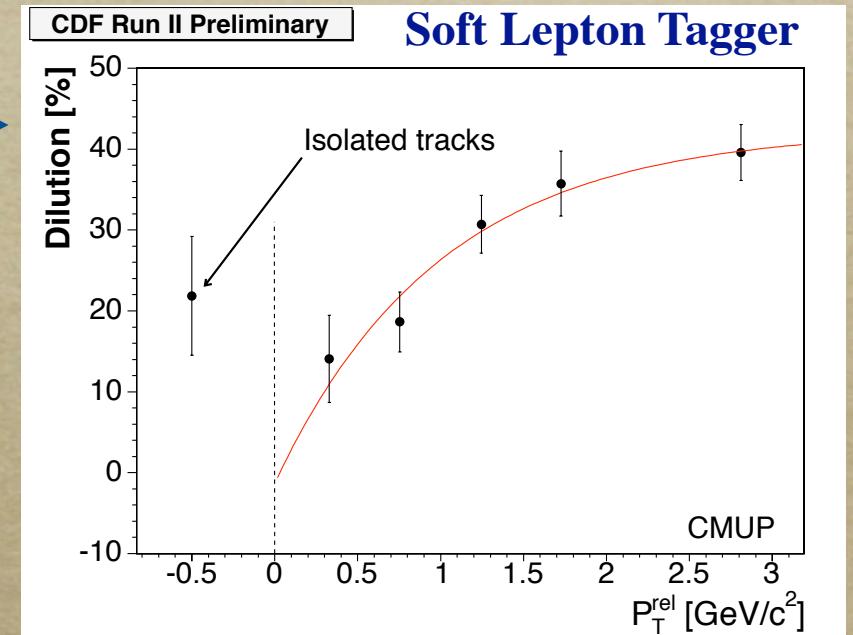
Efficiency, ϵ = fraction of tagged events

Dilution, D = measure of taggers' purity

Effective statistics for mixing is $N_s \epsilon D^2$

- OSTs tuned in lepton+SVT track
high statistics inclusive B sample
- Performance same for all B species
- Measure dilution scale factors in
 $D(3)\pi$ and $\Lambda\bar{D}$ samples of B^+ , B^0
- to account for kinematic differences
in mixing samples relative to l+SVT

$$D = \frac{\text{correct tags} - \text{incorrect tags}}{\text{correct tags} + \text{incorrect tags}} = 1 - 2 \cdot P_{\text{mistag}}$$



Knowledge of tagging dilution is necessary input for B_s analysis!

B^0 mixing Δm_d

SEMILEPTONIC MODES

Δm_d [ps $^{-1}$]
 $0.511 \pm 0.020 \pm 0.014$

ϵD^2 [%]
 $1.55 \pm 0.08 \pm 0.03$

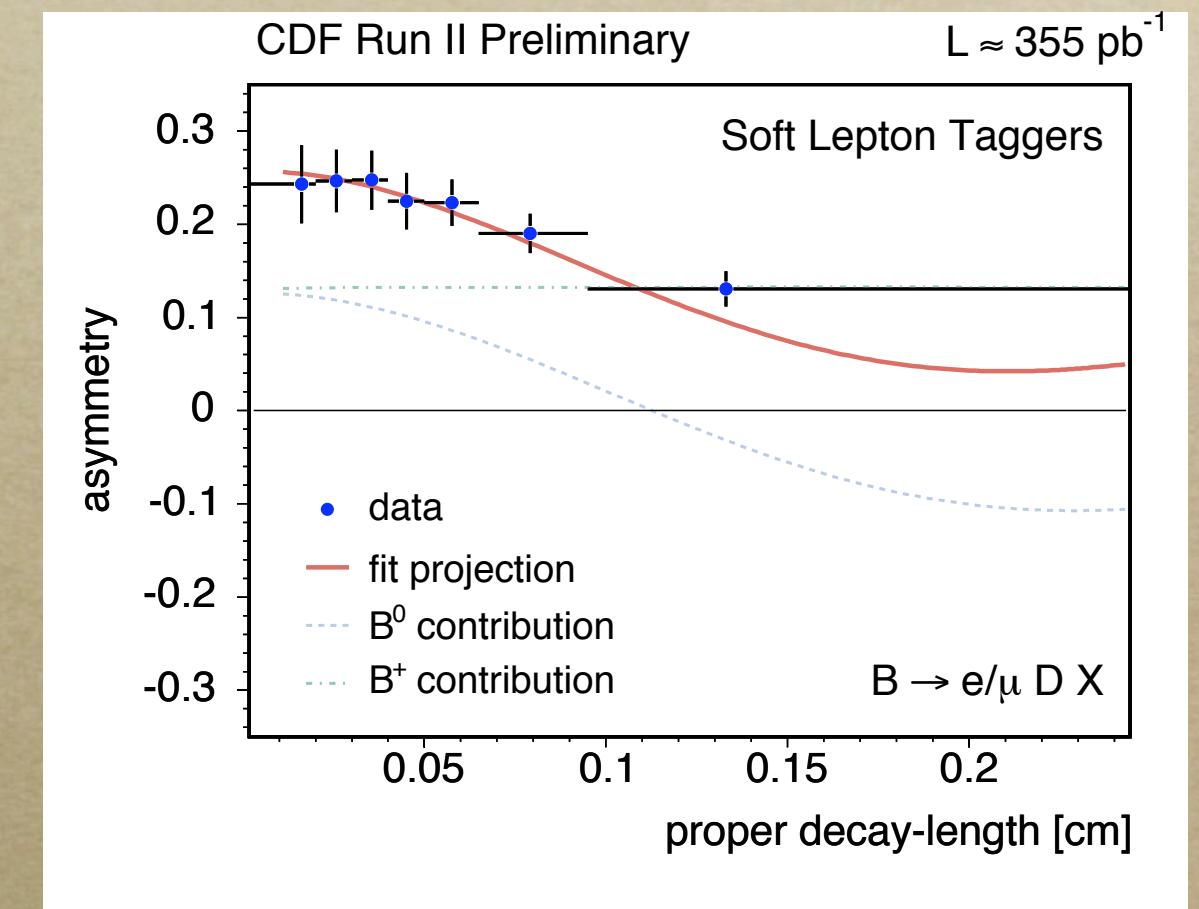
HADRONIC MODES

Δm_d [ps $^{-1}$]
 $0.536 \pm 0.028 \pm 0.006$

ϵD^2 [%]
 $1.55 \pm 0.16 \pm 0.05$

[PDG 2005]
 $\Delta m_d = 0.505 \pm 0.005$ ps $^{-1}$

$$P \sim 1 - S_D \cdot D \cdot \cos(\Delta m_d t)$$



Amplitude Fit

Likelihood model

Perform unbinned likelihood fit using event information:

mass, proper decay-time t and σ_t , tagging decision and dilution

Introduce PDFs describing all signal and background components

Example: signal PDF in ct-space for tagged events (for hadronic modes $k=1$, $F(k)=1$):

Normalization	Lifetime	Tagging	Mixing	ct-resolution	ct-efficiency	k-factor
\downarrow	\downarrow	\downarrow	\downarrow	\downarrow	\downarrow	\downarrow

$$\mathcal{P}(t) = \frac{1}{N} \Gamma k e^{-\Gamma kt'} \left\{ \frac{1 \pm AD \cos(\Delta m_s k t')}{2} \right\} \otimes G(t - t'; \sigma_t) \cdot \epsilon_{ct}(t) \otimes \mathcal{F}(k)$$

$N = \int \Gamma k e^{-\Gamma kt'} \otimes G(t - t'; \sigma_t) \cdot \epsilon_{ct}(t) \otimes \mathcal{F}(k) dt$
(PDF normalization, analytical calculations)

Amplitude (A, σ_A)

Amplitude method

Introduce Amplitude into likelihood: $P \sim 1 \pm A D \cos(\Delta m_s t)$

Perform Amplitude fit for spectrum of Δm_s probed values

expect: $A \sim 1$ for true Δm_s value and $A \sim 0$ away from true value

Apply method to B^0 mixing case

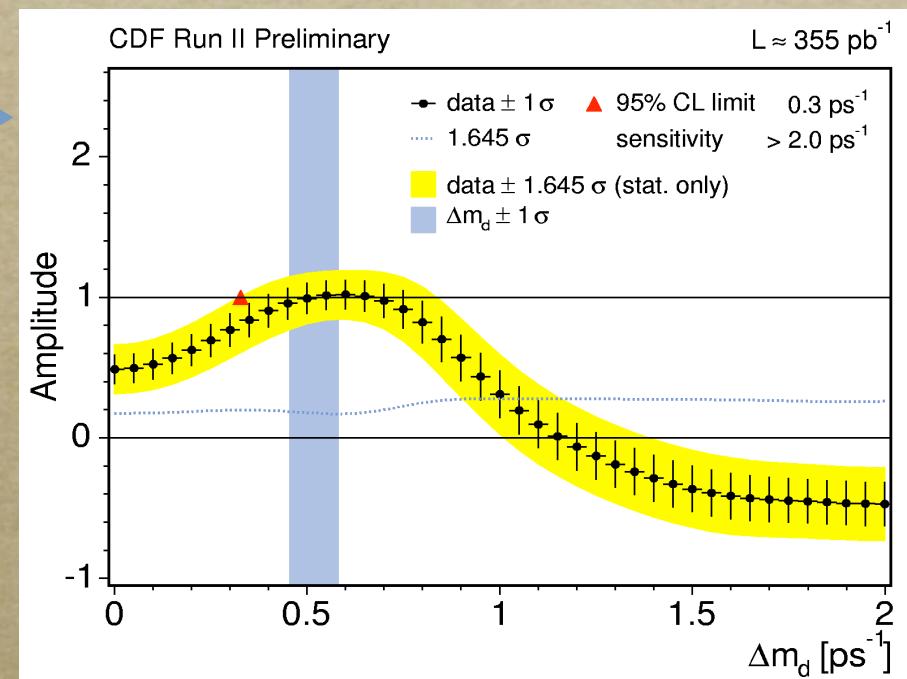
- 95% CL exclusion condition

$$A + 1.645 \sigma_A < 1$$

- 95% CL sensitivity condition

$$1.645 \sigma_A = 1$$

$$\left[\int_{-\infty}^{1.645} e^{-\frac{x^2}{2}} dx = 0.95 \right]$$

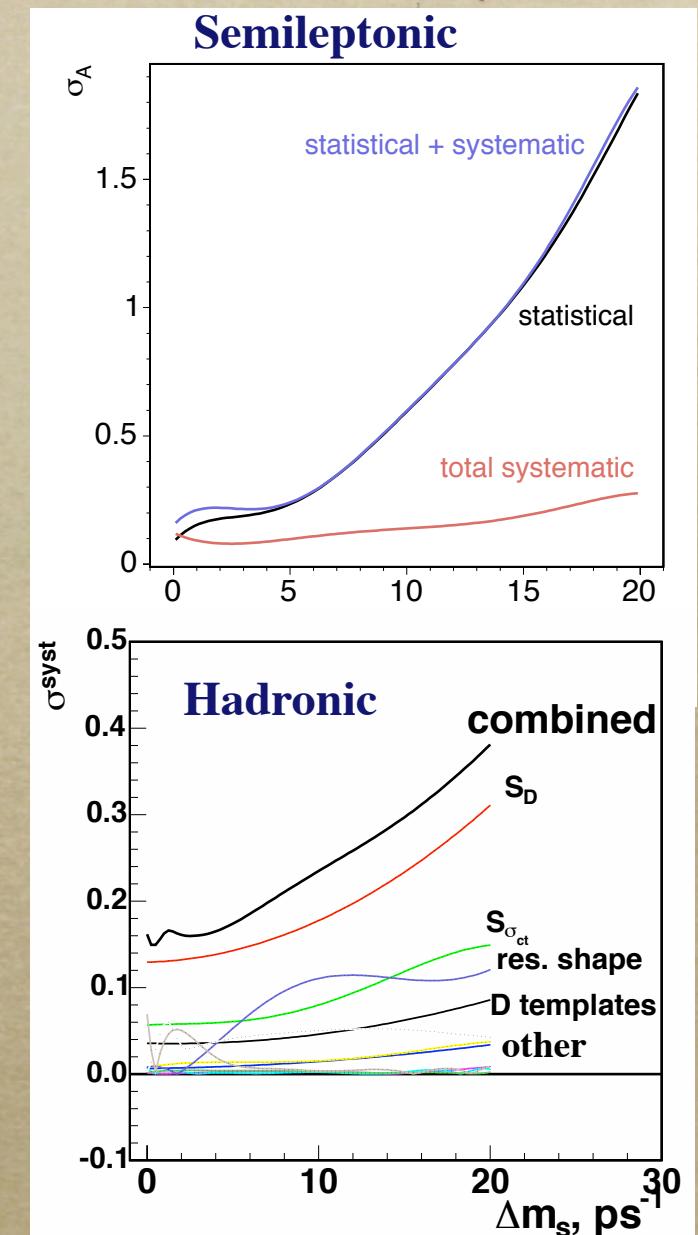


B^0 example scan, winter 2005 analysis

Summary of Systematic uncertainties

- Analysis is statistics dominated
 - Dominant systematics contributions
 - absolute dilution calibration (**Hadronic**)
 - prompt background fraction (**Semileptonic**)
 - ▶ Statistics increase → systematics will reduce
 - Evaluate by fitting many toy MC samples
 - with modified likelihood configurations
 - take shifts in A and in statistical error σ_A
- [H.G. Moser, A. Roussarie, NIM **A384** (1997)]

$$\sigma_A^{syst} = \Delta A + (1 - A) \frac{\Delta \sigma_A}{\sigma_A}$$

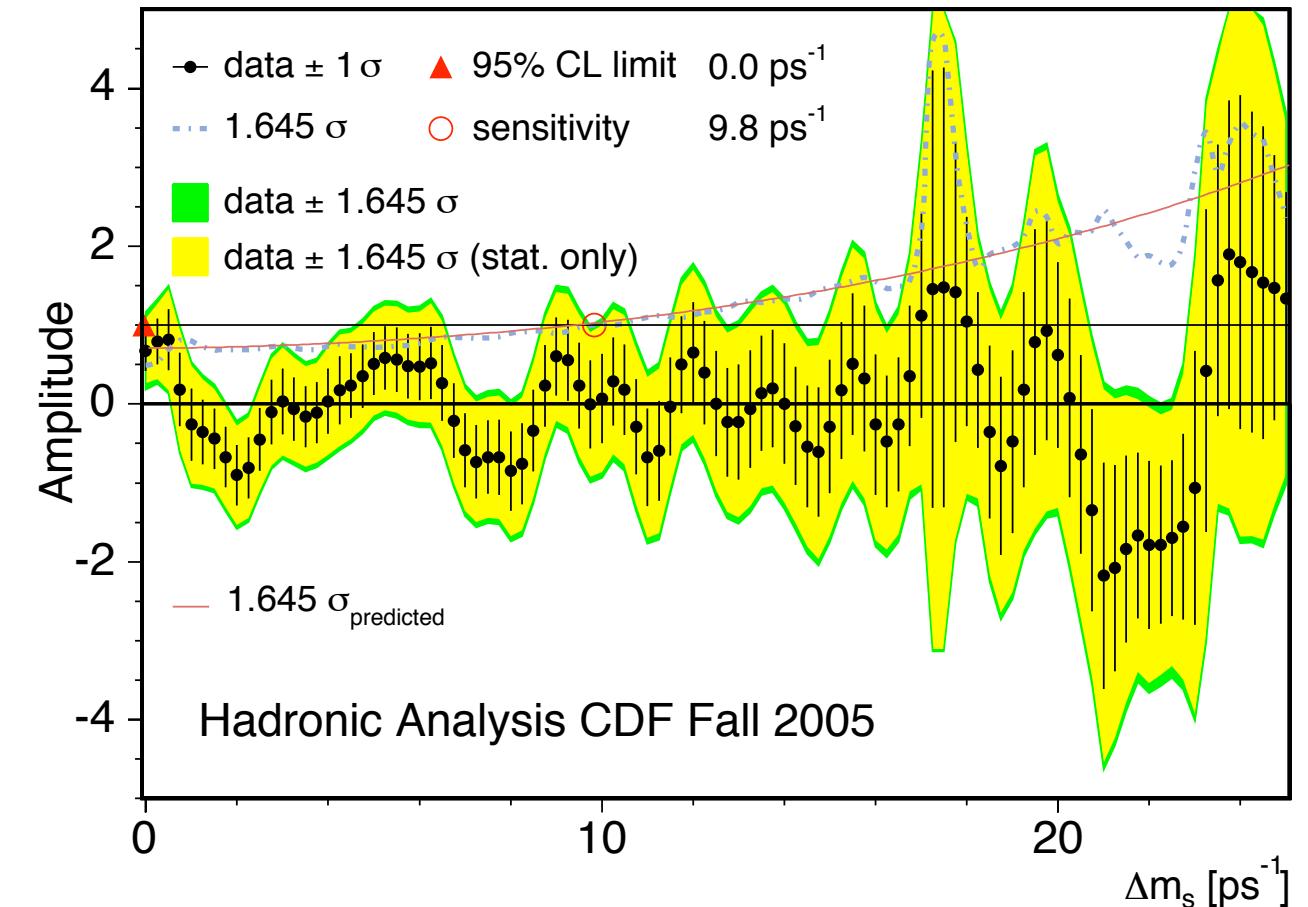


Amplitude scan (i)

Hadronic modes

95% CL LIMIT
0.0 ps⁻¹

SENSITIVITY
9.8 ps⁻¹

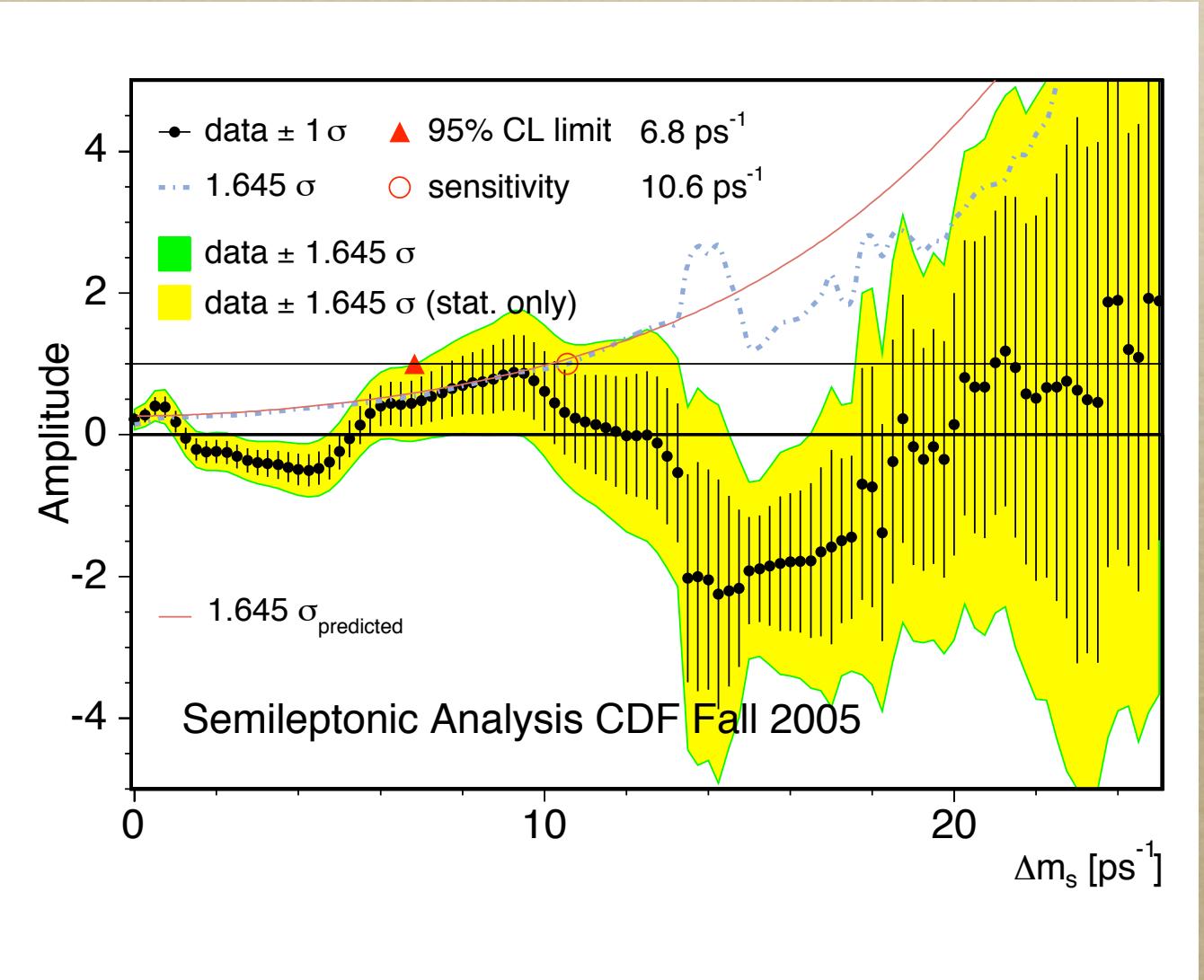


Amplitude scan (ii)

Semileptonic modes

95% CL LIMIT
6.8 PS⁻¹

SENSITIVITY
10.6 PS⁻¹



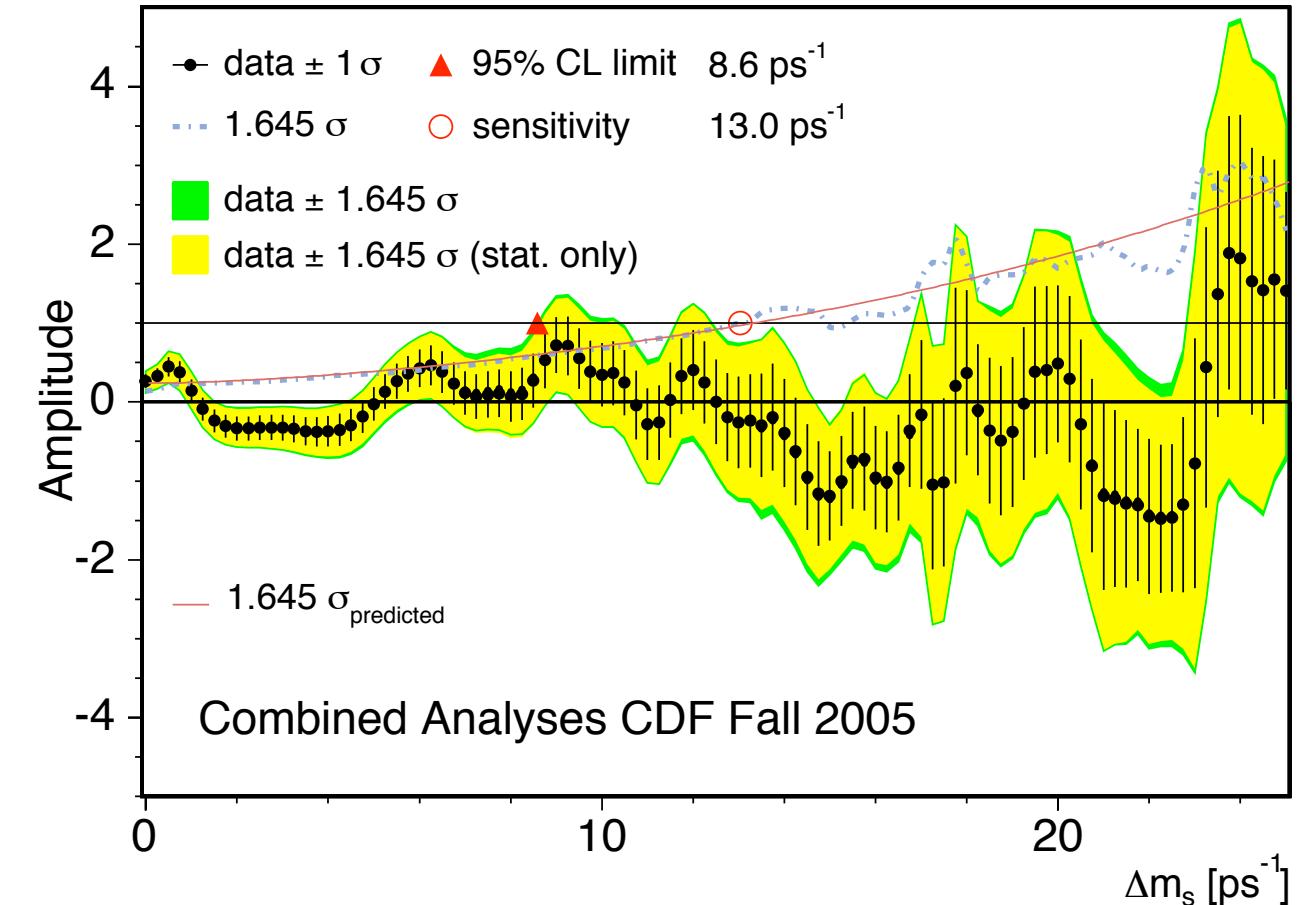
Amplitude scan (iii)

Combined
semileptonic+hadronic

modes

95% CL LIMIT
 8.6 ps^{-1}

SENSITIVITY
 13.0 ps^{-1}

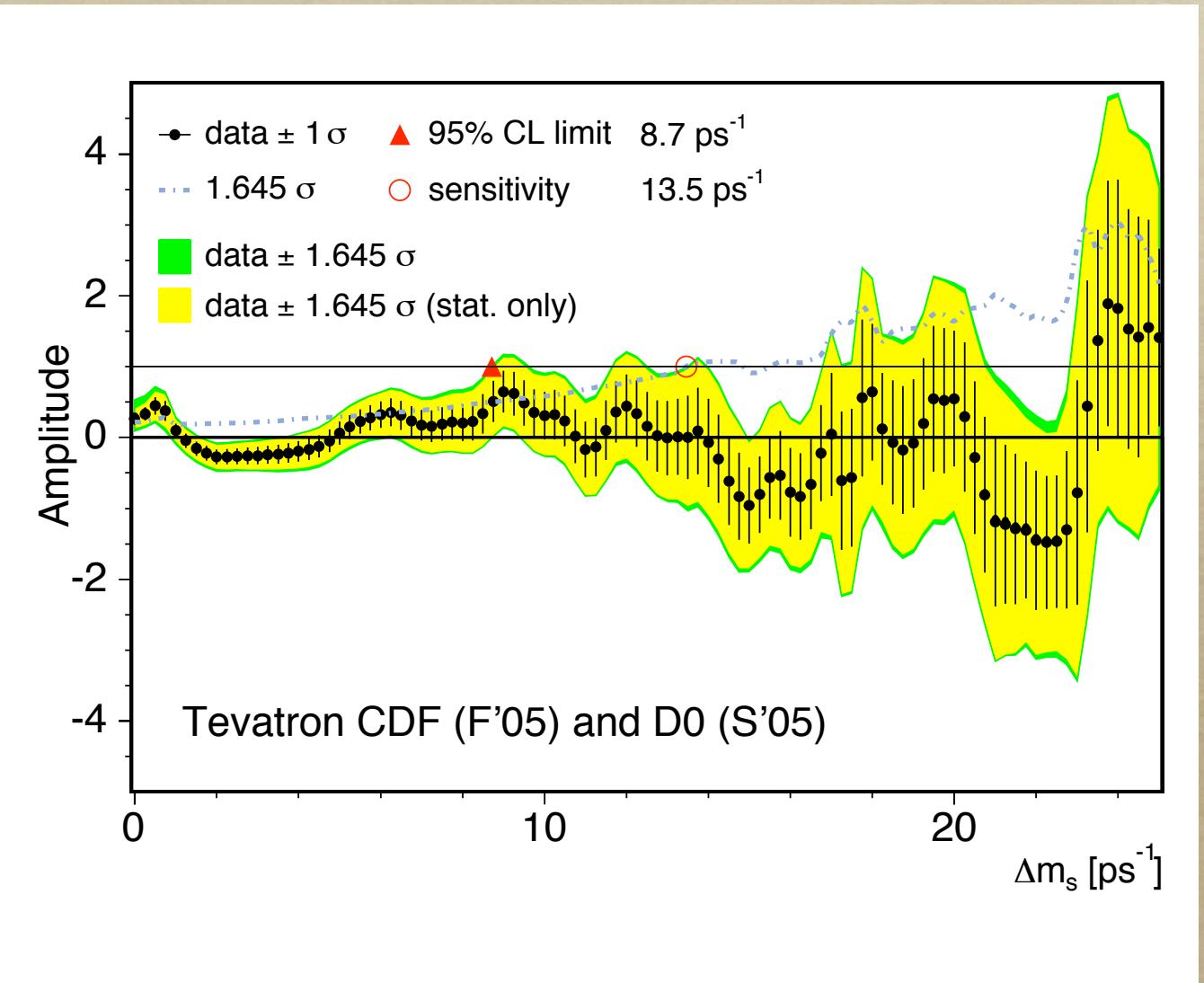


Amplitude scan (iv)

Combined
Tevatron

95% CL LIMIT
 8.7 ps^{-1}

SENSITIVITY
 13.5 ps^{-1}

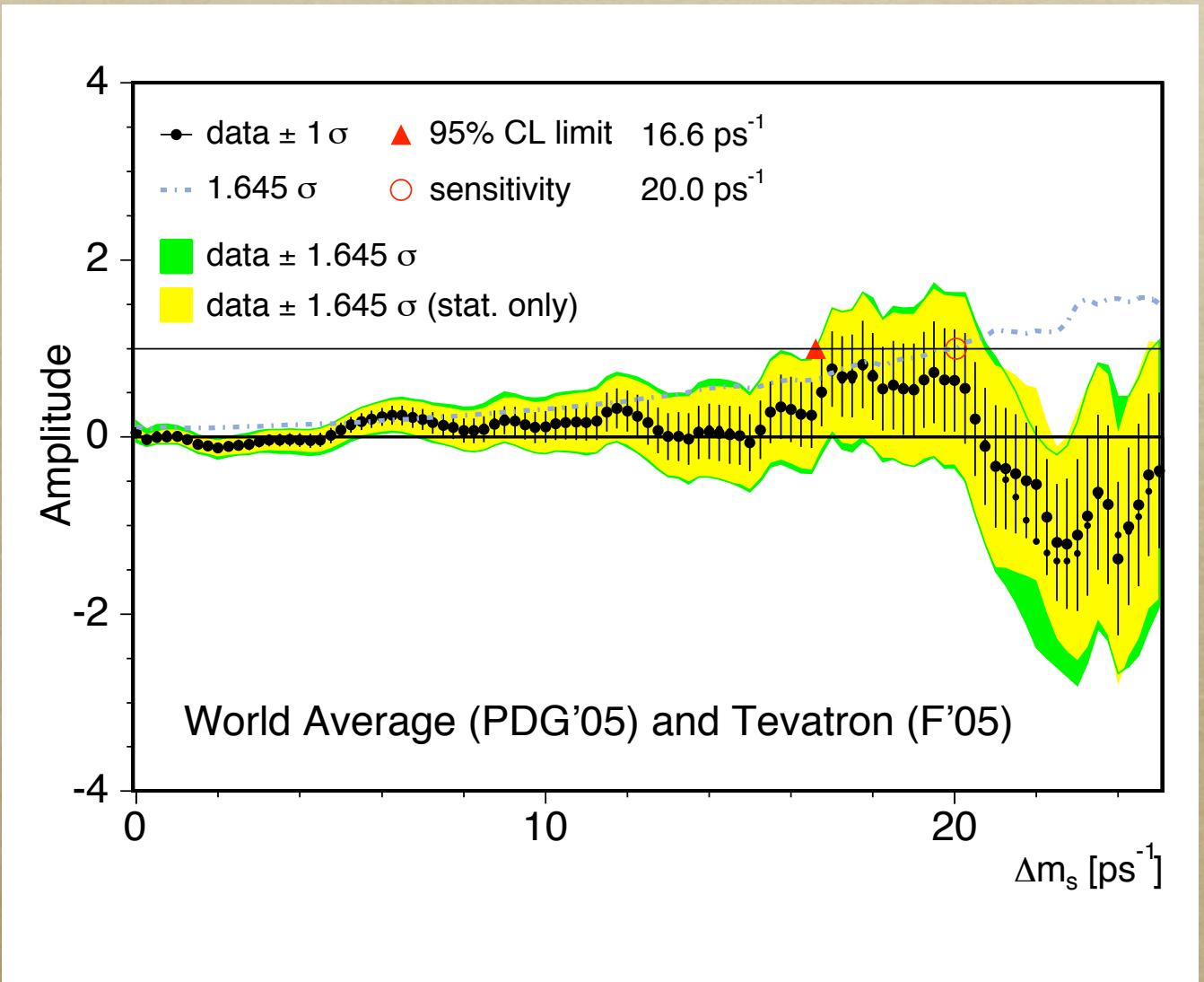


Amplitude scan (v)

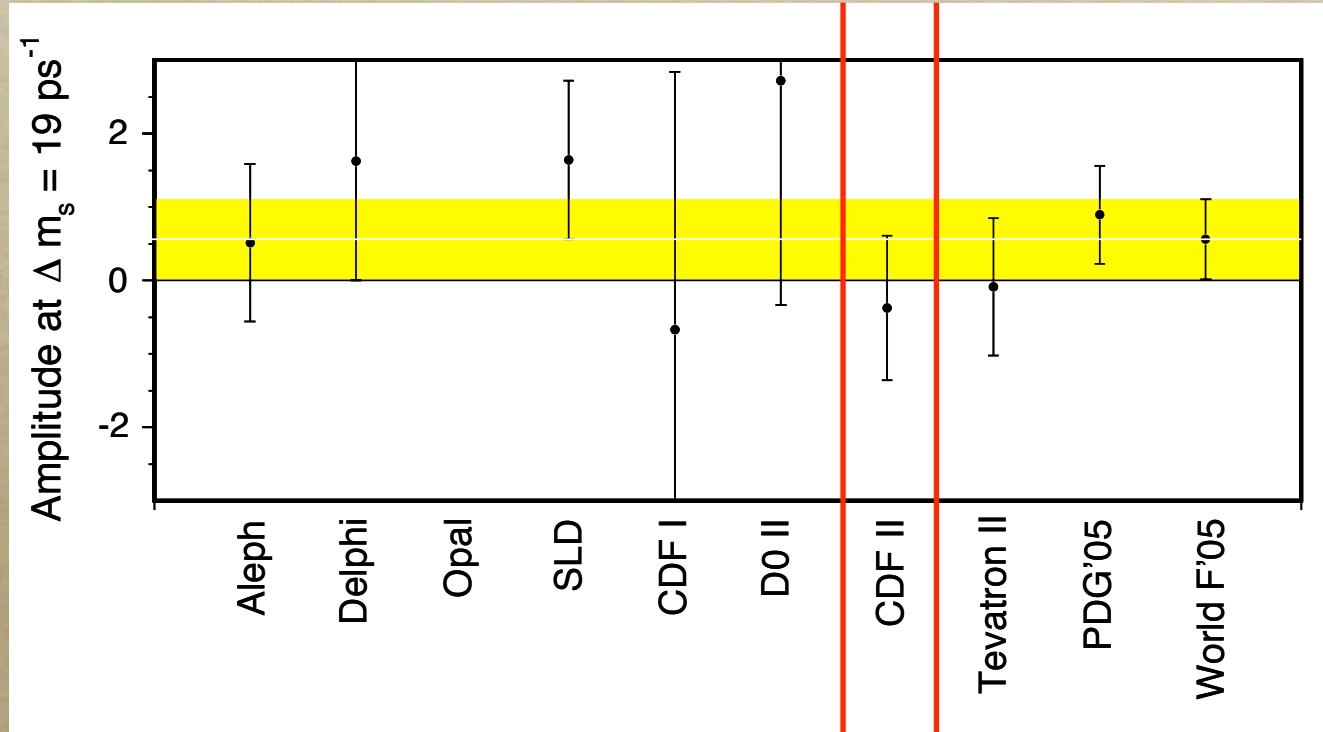
Combined
Tevatron
& World

95% CL LIMIT
 $14.5 \text{ ps}^{-1} \rightarrow 16.6 \text{ ps}^{-1}$

SENSITIVITY
 $18.2 \text{ ps}^{-1} \rightarrow 20.0 \text{ ps}^{-1}$



Amplitude comparison at $\Delta m_s = 19 \text{ ps}^{-1}$



Updated averages of amplitude measurements
in favored SM Δm_s region
performed by various experiments

CKM fit

Making use of the amplitude scan

Unitarity Triangle CKM fit

[L.V.-Sevilla, N.L.]

- Exclusion limit and sensitivity provide only a very short summary of the results of the analysis
- The full information in the amplitude scan is used to construct a *prior* ‘pdf’ for Δm_s in the CKM fit

Constraints to the CKM matrix parameters ($\bar{\rho}, \bar{\eta}$)

$$\Delta m_s \rightarrow (1 - \bar{\rho})^2 + \bar{\eta}^2 = a \cdot \frac{1}{\Delta m_s}$$

$$\Delta m_d \rightarrow (1 - \bar{\rho})^2 + \bar{\eta}^2 = b$$

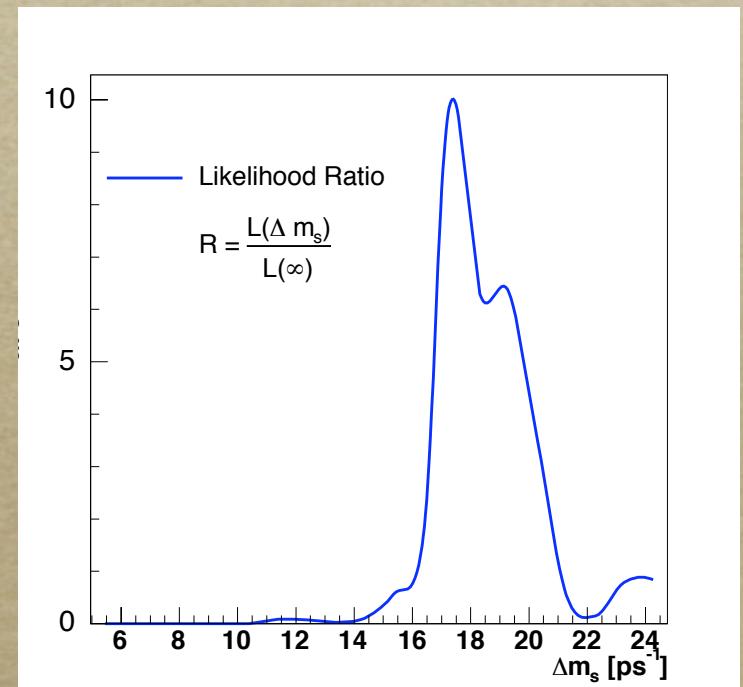
$$\left| \frac{V_{ub}}{V_{cb}} \right| \rightarrow \bar{\rho}^2 + \bar{\eta}^2 = c$$

$$|\epsilon_k| \rightarrow \bar{\eta}[1 + d(1 - \bar{\rho})] = e$$

$$\sin(2\beta) \rightarrow \frac{1\bar{\rho}(1 - \bar{\rho})}{\bar{\eta}^2 + (1 - \bar{\rho})^2} = f$$

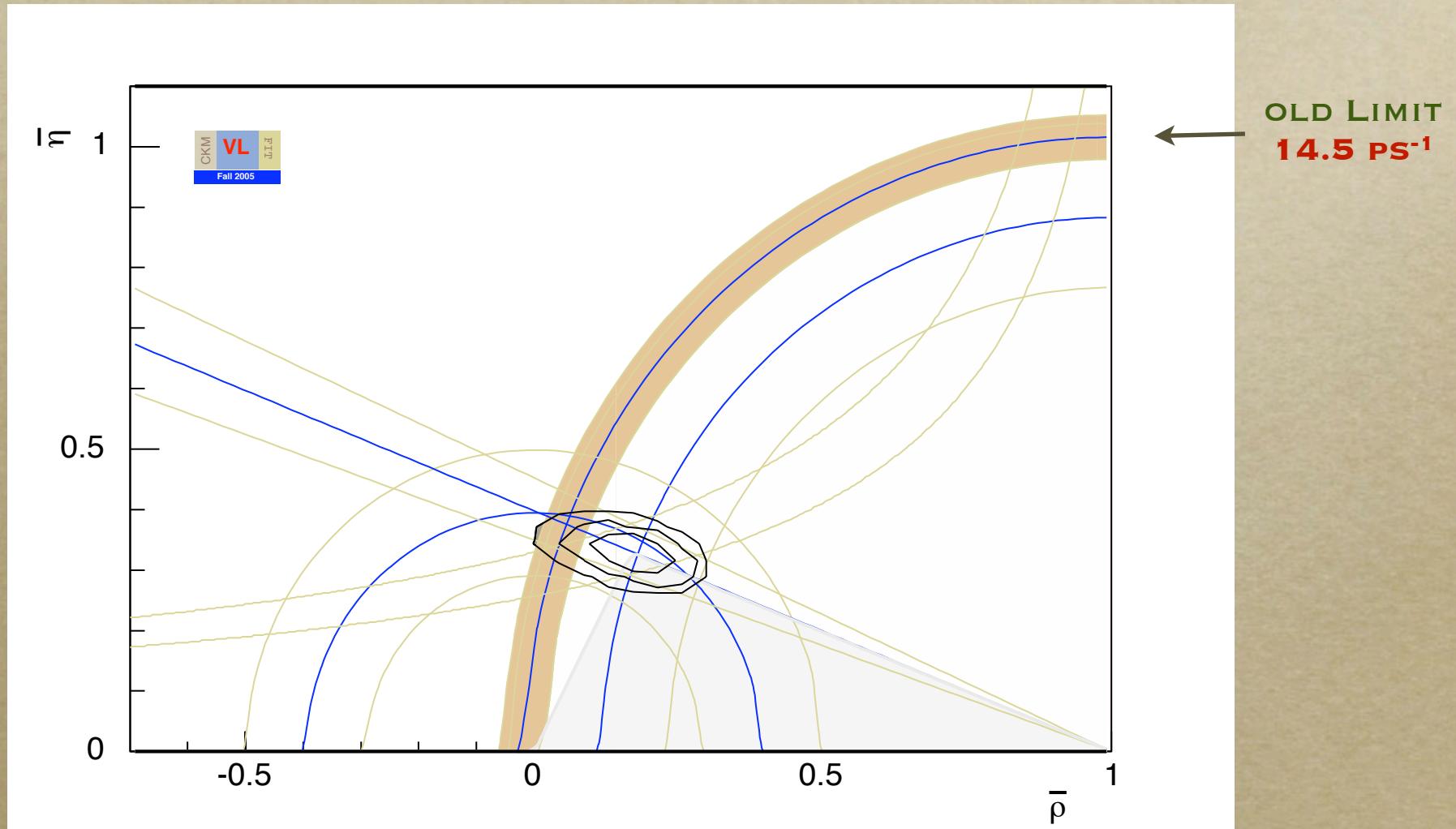
(A, σ_A) scan

$$R(\Delta m_s) = e^{\frac{A - \frac{1}{2}}{\sigma_A^2}}$$



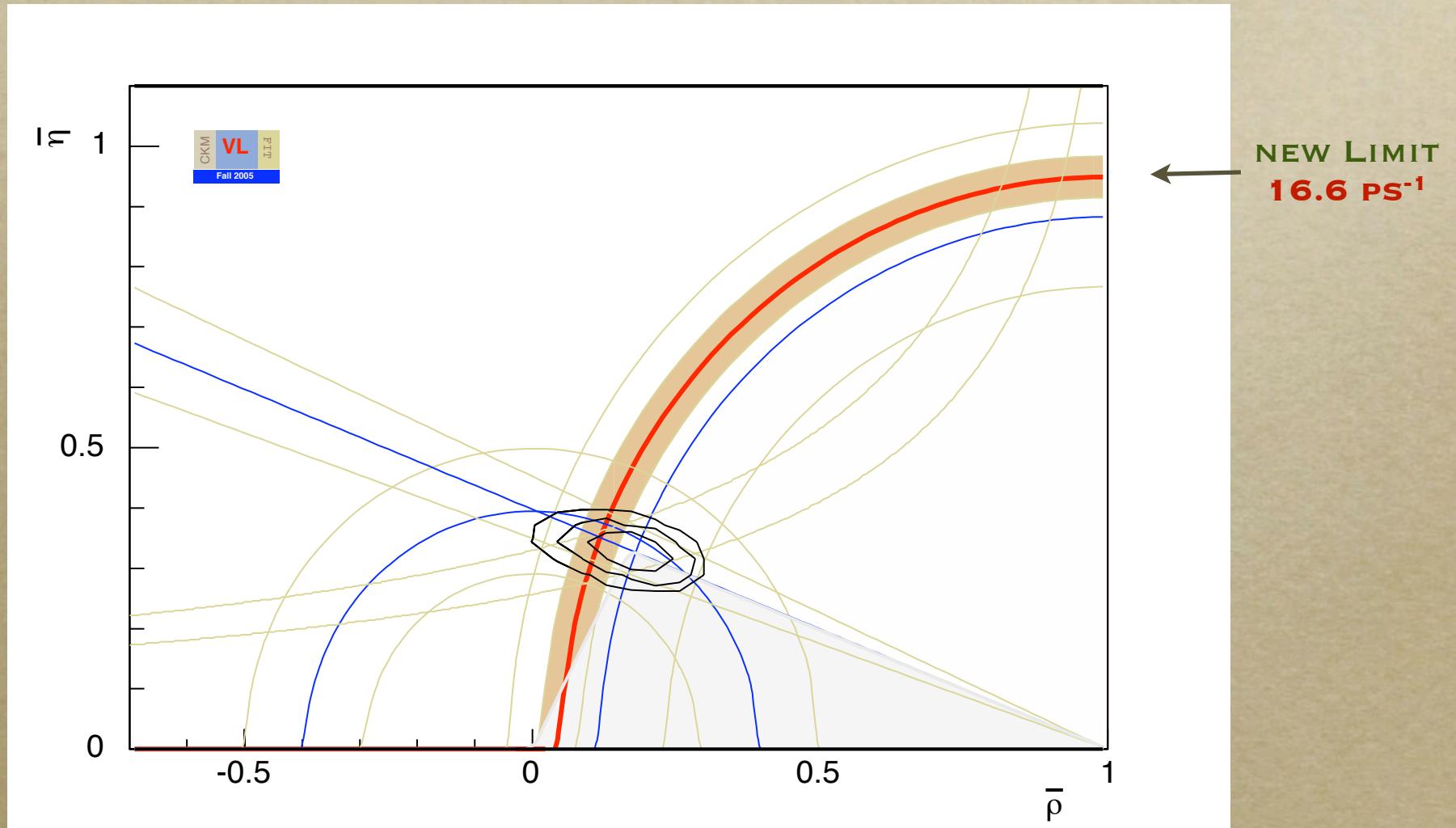
Making use of the amplitude scan

Unitarity Triangle CKM fit



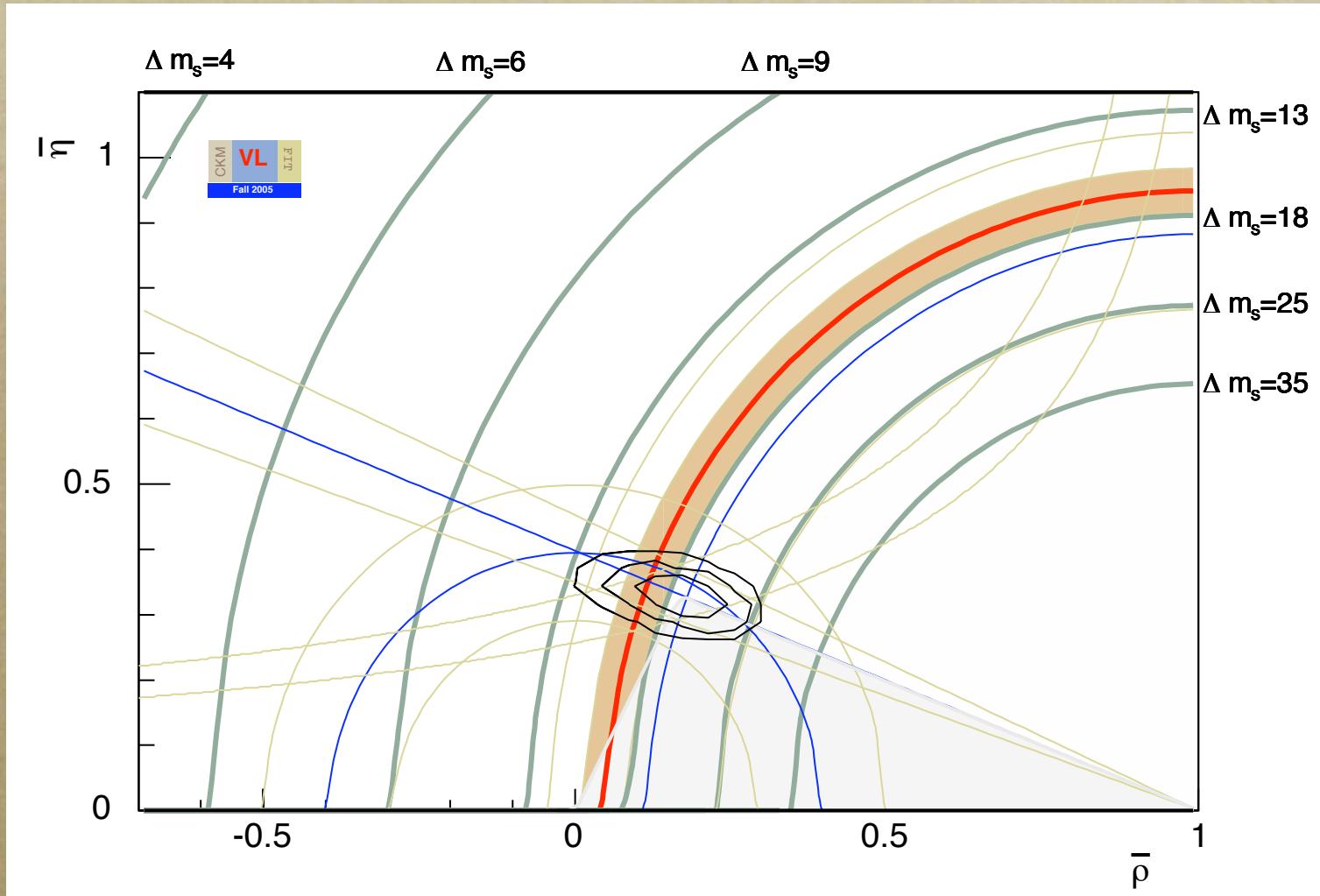
Making use of the amplitude scan

Unitarity Triangle CKM fit



Making use of the amplitude scan

Unitarity Triangle CKM fit



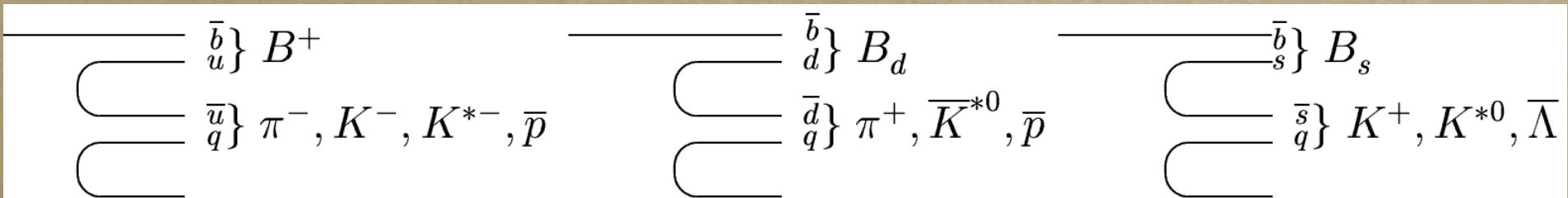
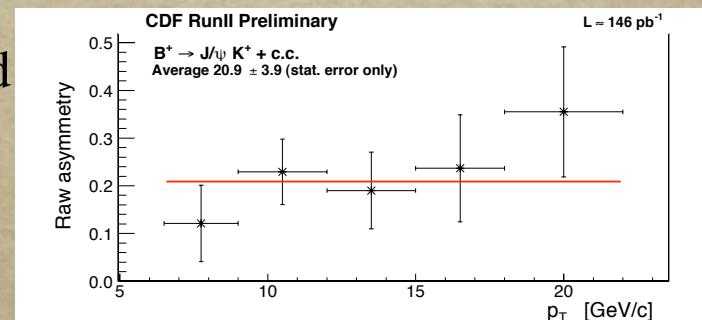
Improvement - sst

Same Side Tagging

- The SST method is based on flavor-charge correlations between the B meson and particles produced in **fragmentation**
- Depends on B species: B^+ , B^0 , B_s - unlike OSTs
- Cannot measure **D** on data unless mixing is observed
- Need to rely on Monte Carlo predictions: tune Pythia
- Improve by using PID (dE/dx , TOF) to identify kaons
- Dilution parameterization and SST+OST implemented
- Very significant improvement in **ϵD^2** is expected
- Started evaluation of systematic effects

D	
B^+	0.21 ± 0.01
B^0	0.13 ± 0.02
B_s	?

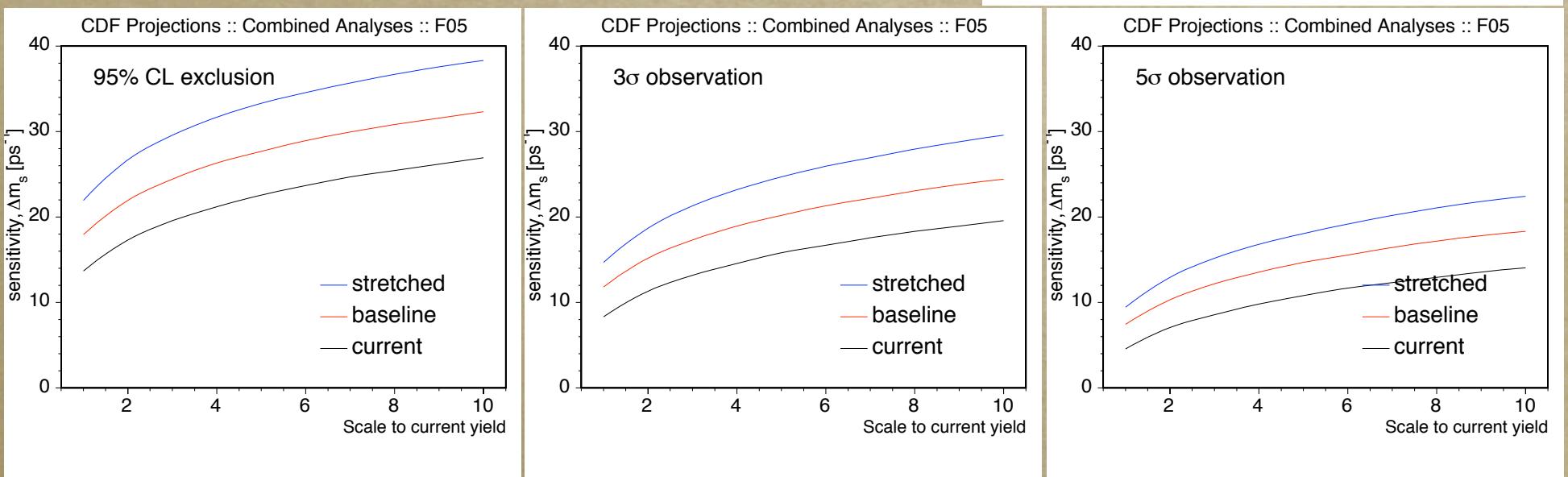
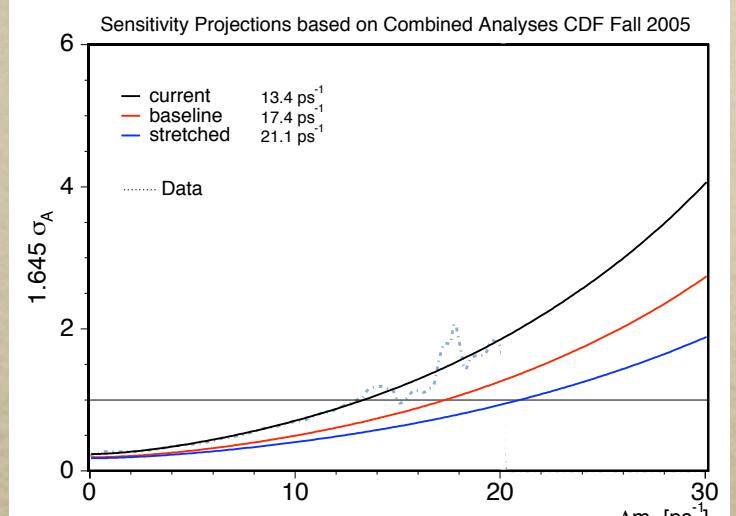
First results in exclusive modes Spring 2003:



Sensitivity projections

SST		
	ϵD^2	σ_t
baseline	0.035	-0%
stretched	0.050	-10%

Assumed inputs for F'05 projections



Conclusions

- Established lifetime and mixing analysis techniques
- Performed first B_s mixing analyses at CDF Run II
 - ▶ exclusion limit **8.6 ps⁻¹** and sensitivity **13.0 ps⁻¹** [95% CL]
- Have already significant impact in world average
 - ▶ combined limit **16.6 ps⁻¹** and sensitivity **20.0 ps⁻¹** [95% CL]
- Same Side Tagging expected to provide big improvement
 - ▶ 3σ exclusion or evidence reachable soon in favored region

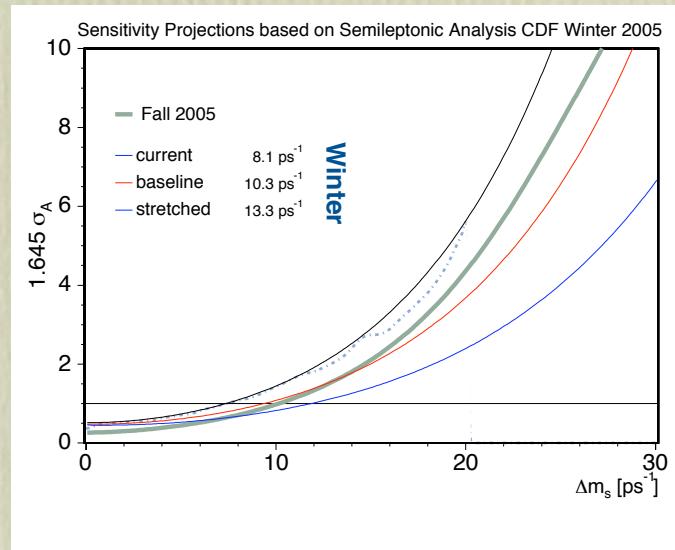
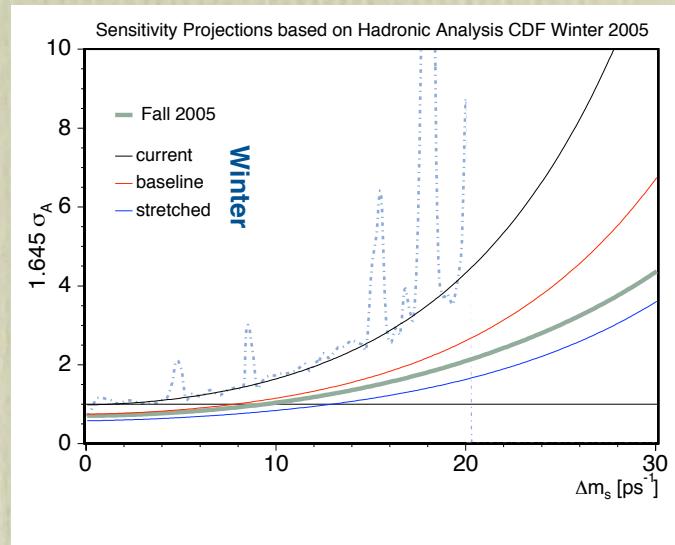
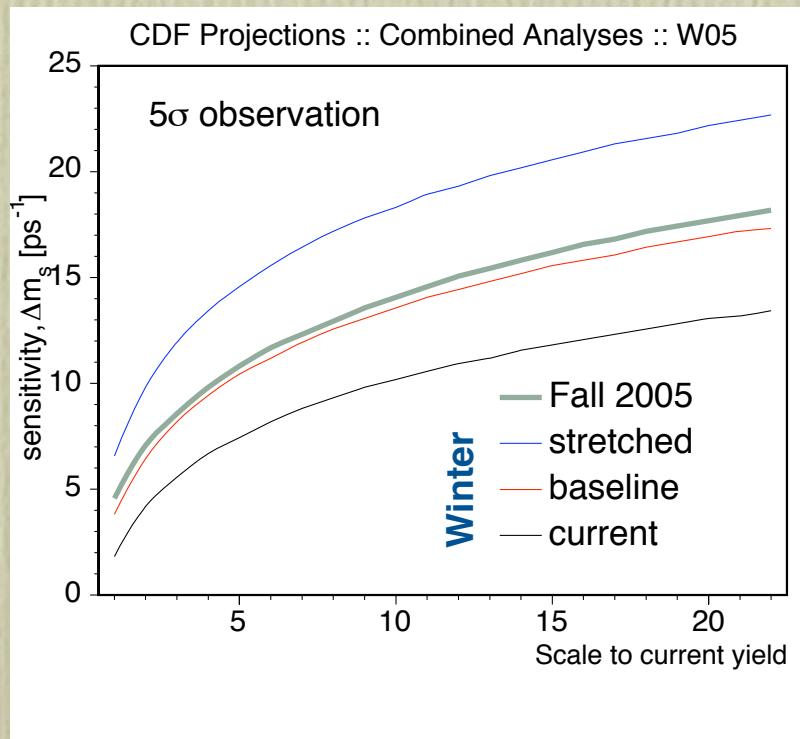
THE B_S MIXING MOVIE

Backup

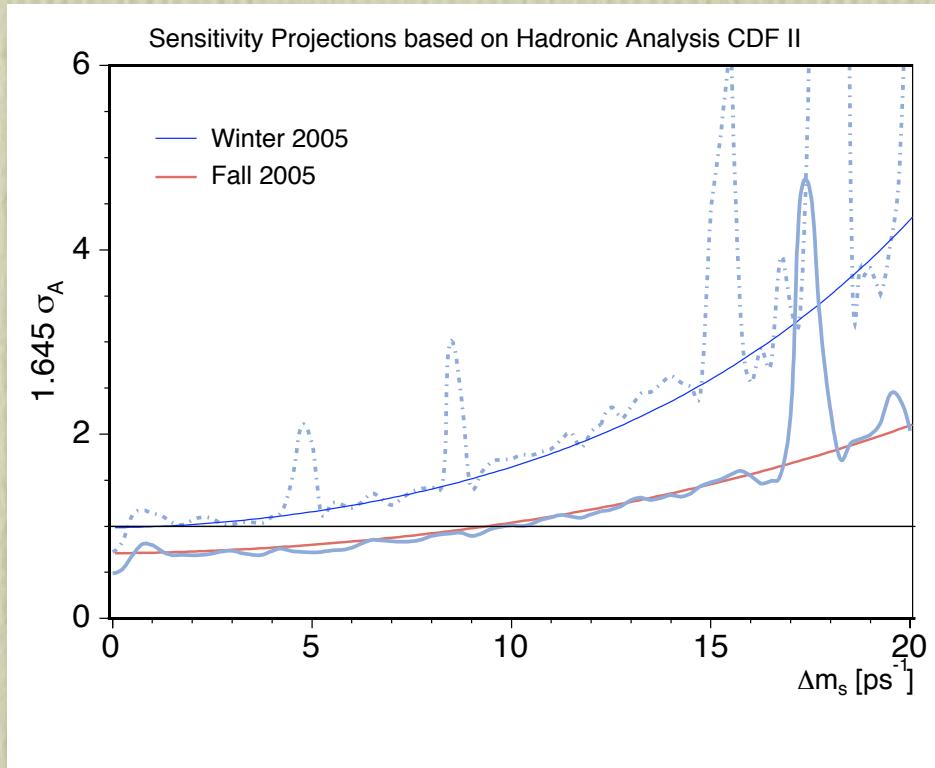
A look at Winter'05 projections

Assumed improvements for W'05 projections

	ϵD^2	σ_t
baseline	+0.01	-10%
stretched	+0.03	-20%



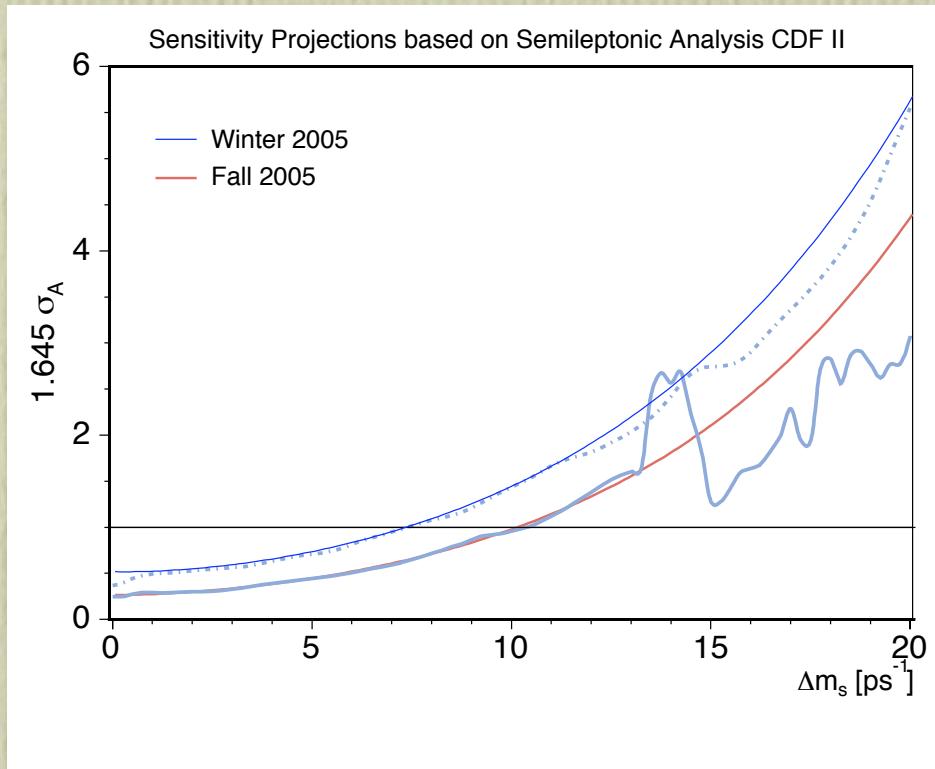
Hadronic significance



	W'05	F'05
sample	TTT	TTT
yield	900	1100
S/B	1.7	3.4
σ_t	113 fs	96 fs
ϵD^2	1.12%	1.55%
Sensitivity	0.4 ps^{-1}	9.8 ps^{-1}

[average values]

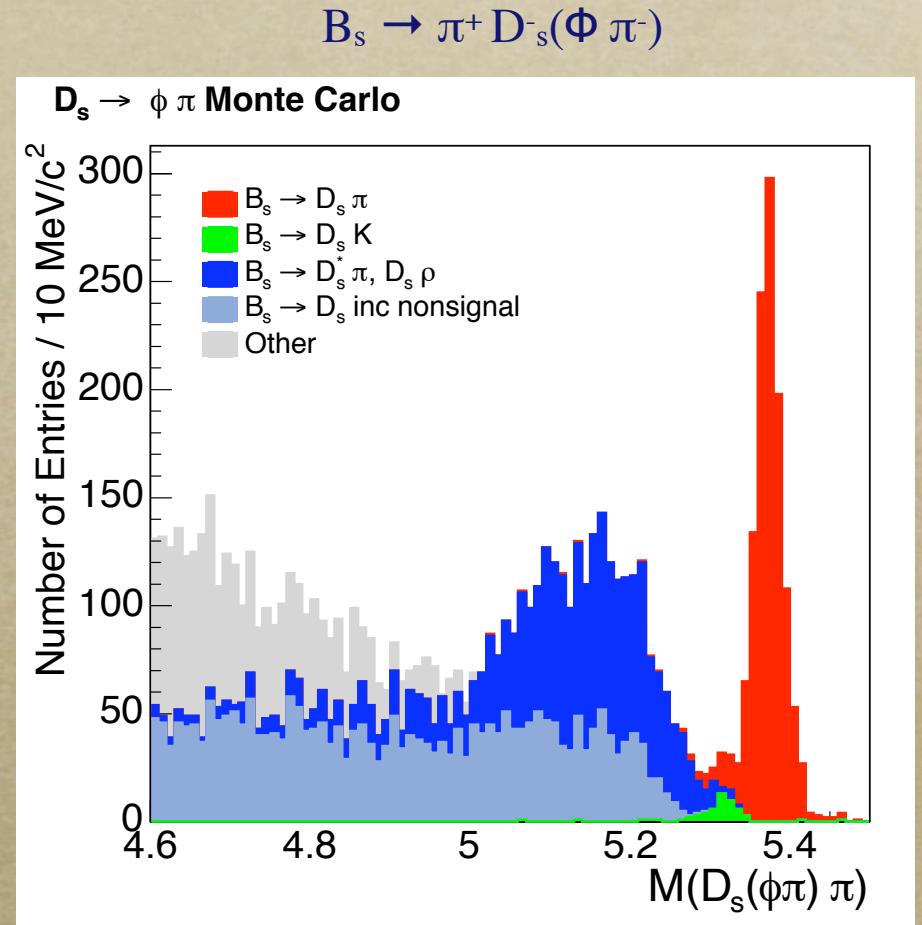
Semileptonic significance



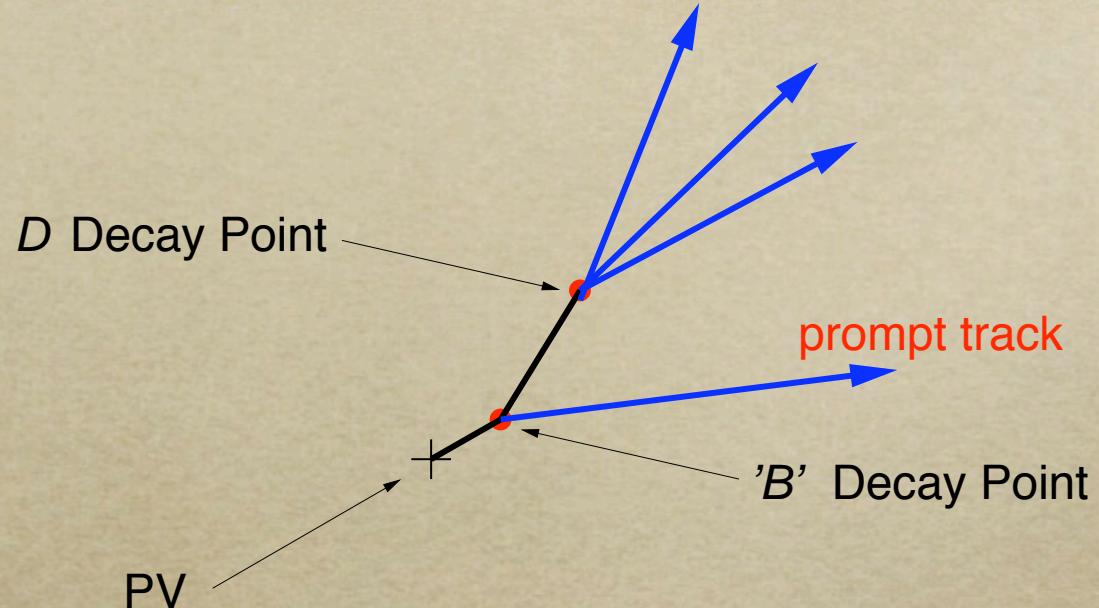
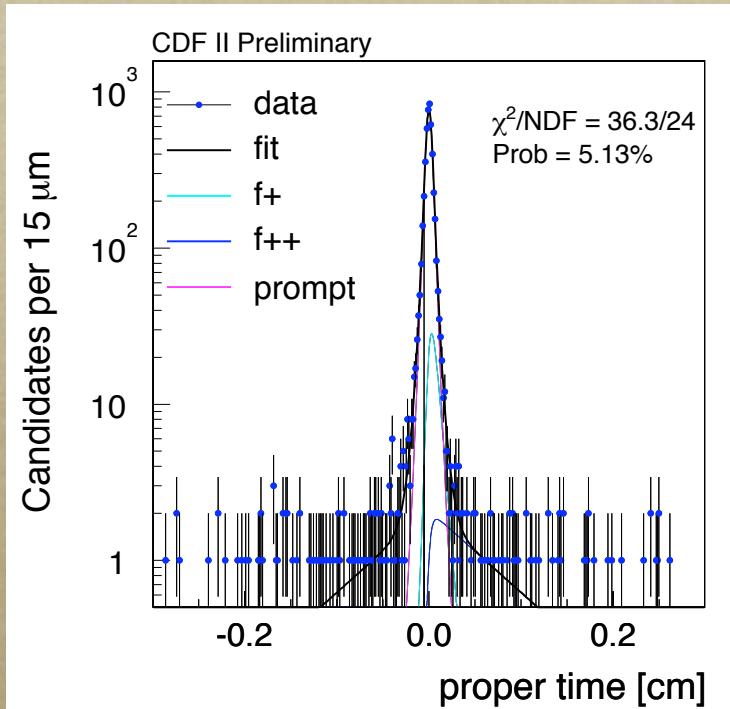
	W'05	F'05
sample	l+SVT	TTT
yield	7700	15000
S/B	1.9	2.3
σ_t	167 fs	157 fs
ϵD^2	1.43%	1.58%
Sensitivity	7.4 ps^{-1}	10.6 ps^{-1}
[average values]		

Sample composition

- Combinatorial background
 - involving non-B tracks
- Partially reconstructed candidates
 - e.g. $D_s^* \rightarrow D_s \gamma, \rho \rightarrow \pi\pi$
- Misreconstructed candidates
 - e.g. $B_s \rightarrow D_s K, B_s \rightarrow l^+ D_s$
- Physics background in $B_s \rightarrow l^+ D_s^- X$
 - real D_s^- with: fake l^+ or l^+ from cc event
 - determined from $l^+ D_s^-$ mass distribution



Vertex resolution calibration



- Vertex fitter errors need to be corrected - **scale factors**
- Create unbiased calibration sample
 - ⦿ require D to trigger and add unbiased track (not triggered)
- PV position has to be zero :: extract scale factor per event
- Fit: **prompt** unit Gaussian + negative tail + long-lived component

B physics in p \bar{p} collisions

- Huge B production cross section
 - $\sigma(p\bar{p} \rightarrow bX, |\eta| < 0.6) = 17.6 \pm 0.4 \text{ (stat)} \pm 2.5 \text{ (syst)} \mu\text{b}$
 - 3 orders of magnitude higher than at $e^+e^- \rightarrow \gamma(4s)$
- Various b-hadron species are produced
 - $B^+, B^0, B_s, B_c, \Lambda_b, \Xi_b, B^*, B^{**}$
- Immersed in large inelastic background
 - inelastic cross section $\sim 100 \text{ mb}$
 - challenge: pick 1 B decay from $\sim 10^3$ QCD events
- Spectrum of c.o.m. energies
 - as opposed to well defined \sqrt{s} at e^+e^- colliders

Heavy and excited
B states currently
unique at Tevatron!

Triggering is crucial!